INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 692–702

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

An experimental investigation on the performance characteristics of a hydroxygen enriched gasoline engine with water injection

Y. Karagöz [a,**], L. Yüksek [a], T. Sandalcı [a], A.S. Dalkılıç [b,*]

[a] Automotive Division, Department of Mechanical Engineering, Mechanical Engineering Faculty, Yildiz Technical University, Yildiz, Besiktas, Istanbul 34349, Turkey

[b] Heat and Thermodynamics Division, Department of Mechanical Engineering, Mechanical Engineering Faculty, Yildiz Technical University, Yildiz, Besiktas, Istanbul 34349, Turkey

ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form
28 October 2014
Accepted 2 November 2014
Available online 25 November 2014

Keywords:
Hydrogen
Water injection
Gasoline engine
Alternative fuels

ABSTRACT

In this study, effect of hydroxygen ($H_2 + O_2$) addition on performance and emissions of a gasoline engine was experimentally investigated. Flow rate of hydroxygen gas mixture was adjusted to 0%, 3.75% (2.5% H_2 + 1.25% O_2) and 7.5% (5% H_2 + 2.5% O_2) by-volume of intake charge for entire speed range of the engine. Then, water was injected into the intake manifold of the SI engine to decrease NO_x emissions which were significantly increased with hydroxygen addition. Mass flow ratio of water with respect to gasoline was kept constant as 0.25/1. The original electronic control unit (ECU) wasn't modified and a self-developed ECU was used to control gas injectors (for hydroxygen) and water injector. Initially, gasoline injection rate and intake air flow rate were measured with 50% constant throttle position for entire speed range (1500–5000 rpm) of the test engine and then, calculated hydroxygen and water flow rates were introduced into engine. Total hydrocarbons, oxides of nitrogen and carbon monoxide were measured and COV_{imep}, brake power, brake thermal efficiency and BSEC were calculated. According to test results, brake power, brake thermal efficiency and oxides of nitrogen of the test engine were increased up to 11.7%, 5.9% and 141.1% respectively with hydroxygen addition, whereas COV_{imep}, BSEC, total hydrocarbons and carbon monoxide were decreased up to 15.2%, 5.6%, 74.5% and 59.5% with hydroxygen addition. The maximum increase of NO_x emission with hydroxygen addition was decreased from 141.1% to 82.7% with water injection. However, the improvements in cyclic variation, brake power, brake thermal efficiency, BSEC, THC and CO emission with hydroxygen addition were reduced with water injection.

* *Corresponding author*. Tel.: +90 212 383 2821; fax: +90 212 383 2765.
** *Corresponding author*. Tel.: +90 212 383 2901; fax: +90 212 383 2765.
E-mail addresses: ykaragoz@yildiz.edu.tr (Y. Karagöz), dalkilic@yildiz.edu.tr (A.S. Dalkılıç).

http://dx.doi.org/10.1016/j.ijhydene.2014.11.013

Introduction

Energy is one of the primary research areas, due to the limited source of petroleum-based fuels. Low conversion efficiency and inevitable pollutant production of processes force researchers to investigate alternative sources for energy production. Stringent emission regulations are the other major contributors which encourage industry and institutes to make investment on this research area [1]. In the framework of alternative energy researches, hydrogen (H_2) is one of the most popular and ideal alternative fuel for internal combustion engines [2].

Hydrogen can be used in IC engines as direct pure fuel or supplementary fuel [2,3]. However, pure hydrogen fuelled IC engines suffer from weak power generation because of volumetrically lower heating value of hydrogen compared to gasoline [4]. Also, high level of nitrogen oxides formation which is generated because of high flame temperature of hydrogen is another drawback to commercialize pure hydrogen fuelled SI engines [5]. Therefore, using hydrogen as supplementary fuel in IC engines has lots of advantages because hydrogen enriched hydrocarbon fuels takes positive physicochemical properties of both fuels [6,7].

Hydrogen is regarded as a green additive fuel for use in spark ignition (SI) engines with its favourable combustion properties [8]. Hydrogen's adiabatic flame speed is 5 times higher than gasoline fuel, thus hydrogen enriched gasoline combustion in an SI engine is closer to ideal thermodynamic cycle and it generates higher thermal efficiency [9]. Furthermore, it enhances the homogeneity of hydrogen-gasoline-air mixture thanks to high diffusion coefficient of hydrogen [10]. The flammability limits of hydrogen are wider than gasoline [8,11]. Also, the quenching distance of hydrogen is shorter than gasoline fuel which ameliorates the hydrocarbon emissions [12,13] Latest works about the use of hydrogen as supplementary fuel in the literature are summarized in the following paragraph.

Andrea et al. [14] investigated the effects of engine speed and equivalence ratio of hydrogen blended gasoline combustion. Experiments carried out on a modified carburettor gasoline engine. Authors indicate that the combustion duration decreased with the increase of hydrogen blending fraction. Apostolescu and Chiriac [15] studied the effect of hydrogen addition on the combustion process. It is declared by the authors that the cyclic variation and 10–90% burn duration were greatly reduced when hydrogen mass fraction increased from 1.5% to 3%. The effect of different hydrogen volume fractions on THC, NO_x, thermal efficiency and power output was investigated. According to experimental results, higher thermal efficiency and higher rate of heat release were obtained. Hydrogen usage caused a decrease in THC and CO emissions and an increase in NO_x emissions. Bauer and Forest [16] found out that flame stability of mixed fuel improved with hydrogen addition and lean burn limit of mixed fuel expanded. Lucas and Richards [17] used pure hydrogen in SI engine at idle position, and used hydrogen-gasoline blend at partial loads; thereby thermal efficiency increased by 10%. May and Gwinner [18], used pure hydrogen in SI engine at idle position, used hydrogen-gasoline blend at partial loads and used only gasoline at full load; thereby they obtained 25% improvement at partial loads. Ji and Wang [19] observed effect of 3% and 6% hydrogen addition (volume basis) in SI engine at 1400 rpm engine speed with various excess air ratios on engine performance and emissions. According to acquired results, it is seen that thermal efficiency cycle by cycle variation recovered with hydrogen addition and that CO, CO_2 and HC emissions degraded.

Even though, hydrogen has demonstrated that it improves combustion characteristics of IC engines; the refilling onboard storage problem of hydrogen limits commercially usage of hydrogen [20]. Alternatively, hydrogen can be produced with water electrolysis method which suppresses the necessity of storage device of hydrogen on vehicles. When water electrolyser is used on vehicles, hydrogen can be produced and consumed simultaneously, thus any storage device isn't necessary. Also, the oxygen gas is produced by water electrolyser during the electrolysis of water. Hydrogen and oxygen gas mixture (hydroxygen) which is produced by water electrolyser enhances combustion period of a hydrocarbon fuelled IC engine. Studies about hydroxygen produced by electrolysis are listed in the following paragraph.

Dulger and Ozcelik [21] investigated the effect hydroxygen enrichment and a water electrolyser was used in their study. According to their test results, a significant improvement was achieved in brake thermal efficiency with hydroxygen addition. Bari and Esmaeil [22] used a water electrolyser in a diesel fuel. The produced hydroxygen by electrolyser was used as supplementary fuel and they found out that thermal efficiency of engine increased, HC and CO emissions which are emitted by diesel engine were decreased with increasing hydroxygen percentage. Wang et al. [23] observed effect of 3% hydroxygen ($H_2 + O_2$) addition on engine performance in 1.6 L gasoline engine at 61.5 kPa manifold absolute pressures. According to test results, whenever hydrogen proportion increased in hydroxygen gas mixture, thermal efficiency also increased and HC, CO, NO_x emissions ameliorated.

Solely, hydroxygen or hydrogen use in IC engines has some problems. Because of the lower ignition energy of hydrogen, hydrogen–oxygen mixture gets ignited in the manifold by hot points; this phenomenon is named as backfire [24]. Another important problem is that hydrogen or hydroxygen use in IC engines which generates high level of NO_x. Hydrogen causes the higher in-cylinder temperature which dramatically increases the formation of nitrogen oxides. Some techniques such as EGR, turbo-charging with intercooling, diluents addition, water injection etc. are used to control NO_x formation [25]. Among these methods, water injection is one of the most effective methods to reduce NO_x emissions; also hydrogen can minimize the risk of backfire. On the other hand, high flame speed of hydrogen accelerates pressure rise rate and heat release rate which generate hydrogen knocking [26]. Hydrogen knocking induces high mechanical stresses and hydrogen knocking can be limited with water injection technique. However, the durability tests of using water in IC engines must be done because water use can negatively affect lubricating oil and it will cause corrosion [27]. For these reasons, little water was injected to the engine in our study to protect engine from hazardous effects of water.

Hydrogen use in internal combustion engines (ICE) as an additional fuel is a promising solution for strict emission

regulations due to enhanced combustion characteristics of hydrogen fuel. Nitrogen oxides are the only pollutant products of hydrogen combustion and hence, hydrogen can be classified as a clean alternative fuel compared to petroleum-based hydrocarbons. Introducing hydrogen into ICE as supplementary fuel can improve the regulated tail-pipe emissions. Wang et al. [23] called hydrogen + oxygen gas mixture as hydroxygen in their study. For this reason, hydroxygen definition was also used in our study. The purpose of this study is to investigate performance characteristics and emissions of a hydroxygen enriched gasoline engine. In this study, hydrogen/oxygen molar ratio in gas mixture of hydroxygen is kept constant at 2:1 since water electrolysis method is simulated. Improvement in COV_{imep}, brake power, BSEC, THC and CO values and significant NO_x increase with hydroxygen addition are anticipated from the test results of this study. Lastly, water injection technique is used to limit the increase of NO_x values with hydroxygen addition. Further step of this study may focus on the optimization of engine parameters for pre-determined hydroxygen addition levels. Especially, exact calibration of ignition advance has a great potential to reduce higher NO_x emissions to a target value without deteriorating the engine performance.

Materials and methods

Test system

An automobile spark ignition engine was operated for experiments and its specifications are presented in Table 1. The test engine was modified to operate with hydroxygen gas mixture and water injection. All of the tests were carried out at the Internal Combustion Engines Laboratory in Yıldız Technical University. Also, the test bench was adapted to work with hydrogen and oxygen gases.

Schematic diagram of hydrogen, oxygen and water supplying systems are illustrated in Fig. 1. High pressure hydrogen tank and high pressure oxygen tank were used as hydrogen and oxygen suppliers respectively and they were placed outside of the laboratory. Two-stage high pressure regulators were installed on hydrogen and oxygen tanks to reduce hydrogen and oxygen pressure values to 0.5 MPa from 20 MPa separately. Relief valves were used to prevent possible overpressure. In case of possible overpressure situation, hydrogen and oxygen were separately discharged to the atmosphere using purge lines. Hydrogen and oxygen mass-flow rates were measured by mass-flow meters. Line pressure regulators were used to sensitively adjust and fix the line pressure values as 0.4 MPa both for hydrogen and oxygen. Buffer tanks were installed into both hydrogen and oxygen line to prevent fluctuations of hydrogen and oxygen flow. Prevention of possible backfire problem has been provided by installing check valves into the line before sending hydrogen and oxygen to the gas injectors. Hydrogen and oxygen were mixed together to be sent through gas injectors and multi-point sequential injection system was used to inject hydroxygen in each cylinder separately. All of the equipment of hydrogen and oxygen fuel supplying system was produced from stainless steel. Lastly, a gasoline pump and a gasoline injector were installed to inject water into the intake manifold. Gasoline injector was used as a single point water injection system at the throttle body.

Table 1 – Specifications of the test engine.

Definiton	Value/Specification
Manufacturer & type	Peugeot-1B53318F
Displacement volume (cm^3)	1124
Number of cylinders	4
Bore/stroke (mm)	72/69
Compression ratio	10.2:1
Number of valves per cylinder	4
Rated power	44 kW@5500 rpm
Aspiration	Naturally aspirated
Ignition system	Electronic distributorless
Fuel system	Multi-point fuel injection
Cylinder arrangement	In-line

Schematic diagram of experimental setup is shown in Fig. 2a and the overview of the test engine is presented in Fig. 2b. Test engine was loaded by using a hydrokinetic dynamometer; engine torque was measured with a load-cell. An incremental encoder was used for speed measurement. In case of gasoline injection, the original ECU of the engine was used without any modification while hydroxygen injection was maintained with a self-developed external ECU. A Kistler 6118B pressure transducer with a spark plug having the same properties was screwed into the cylinder head of 4th cylinder to measure in-cylinder pressure. Gasoline flow rate was measured using a Sika VZ 0.2 positive displacement flow meter. Hydrogen and oxygen flow rates were measured using New Flow TMF01 and New Flow TMF00 mass-flow meters respectively. Water flow rate of injector was determined using analytical balance according to signal length of injector. A Bosch gasoline injector was used to inject water into intake manifold. A Keihin LPG-CNG multipoint sequential injection system was used to inject hydroxygen into ports. THC, NO_x and CO exhaust emissions were obtained by using the AVL Dicom 4000 gas analyser. Air consumption was measured with mass air flow sensor used by the management system of the test engine. The load-cell, gasoline flow meter, hydrogen and oxygen mass-flow meters and AVL Dicom 4000 exhaust gas analyser were connected to the NI USB 6215. Also, NI 9223 module was used to acquire in-cylinder pressure. Using LabView software, a program was written for tests and data acquisition cards were connected to computer. Throttle position and engine temperature was monitored via the on-board diagnostic system of the test engine. The accuracies of the measurements and the uncertainties were calculated for the whole speed range of the engine according to Kline and McClintock method [28]. The measurement accuracies of the devices and the calculated uncertainties are listed in Table 2.

Test procedure

All of the tests were performed at steady-state and part-load conditions with 50% constant throttle position. Hydroxygen flow rate was set to 0% (pure gasoline), 3.75% (2.5% H_2 + 1.25 O_2) and 7.5% (5% H_2 + 2.5% O_2) of volumetric fraction of inducted air. Hydrogen and oxygen were introduced into the intake manifold of the test engine with the molar ratio of 2:1.

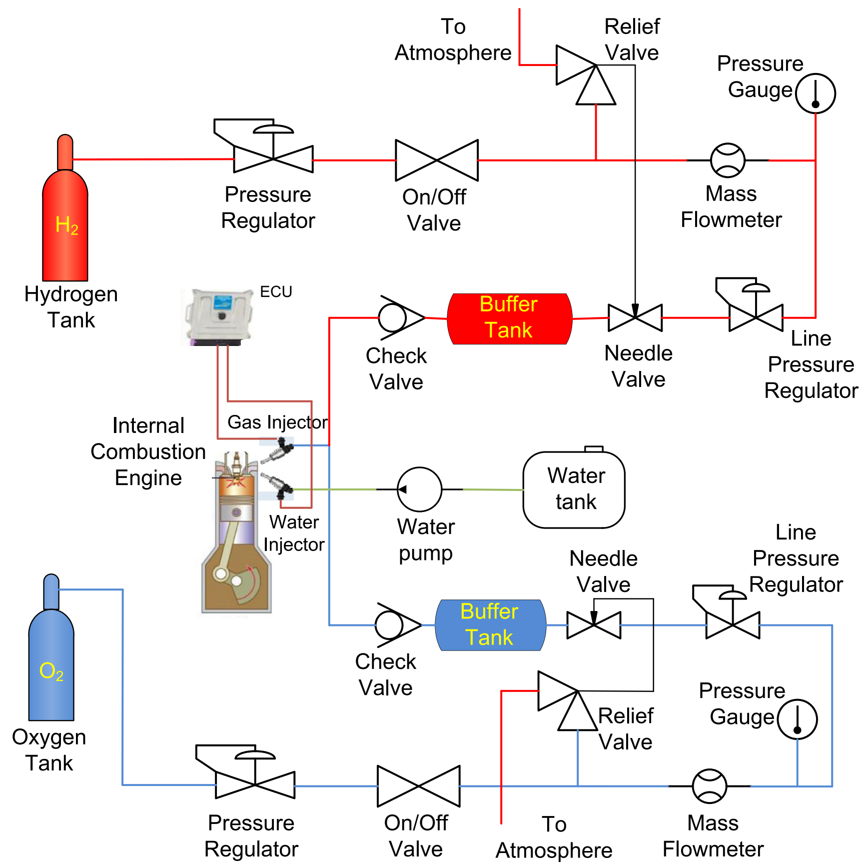

Fig. 1 – Schematic diagram of hydrogen, oxygen and water supplying systems.

Engine speed varied between 1500 and 5000 rpm with 500 rpm equal increment. Then, water was injected into intake manifold with hydroxygen addition. The flow rate of water was kept 25% (mass/mass) of consumed gasoline by the engine. Lots of consequent measurements were averaged after reaching the steady-state test conditions. Also, 100 cycles were used to calculate COV_{imep} for each operating point.

Data reduction

Using collected data sets, the parameters were calculated according to the following equations [3,10,28–31].

The coefficient of variation in the indicated mean effective pressure (imep) was calculated [3]:

$$COV_{imep} = \left[\left(\sqrt{\sum_{i=1}^{m} \left(imep_i - \overline{imep} \right)^2 / m} \right) \Big/ \overline{imep} \right] \times 100\%, \tag{1}$$

where $imep_i$ is the indicated mean effective pressure in the ith cycle of engine in MPa, $\overline{imep}$ is the average value of the indicated mean effective pressures in MPa and m is the number of engine cycle.

The brake torque was calculated according to measured value of load cell connected to moment arm [10]:

$$T = F \times b, \tag{2}$$

where T is the brake torque in Nm, F is the measured load in N and b is the moment arm length in m.

The SI engine was loaded by hydrokinetic dynamometer and absorbed power by dynamometer was calculated depending on brake torque and angular speed [29]:

$$P_b = 2\pi\omega T \times 10^{-3}, \tag{3}$$

where P_b is brake power in kW, ω is the angular speed of the engine in rps and T is the brake torque of the engine in Nm.

The brake thermal efficiency is calculated as a function of brake power, fuel consumption and lower heating value of fuel [30]:

$$\eta_{BT} = \frac{P_b}{\dot{m}_g \times LHV_g + \dot{m}_{H_2} \times LHV_{H_2}}, \tag{4}$$

where η_B is the brake thermal efficiency, P_b is brake power in kW, $\dot{m}_g$ is the mass flow of supplied gasoline fuel in kg/s, $\dot{m}_{H_2}$ is the mass flow of supplied hydrogen fuel in kg/s, LHV_g is the lower heating value of gasoline fuel in kJ/kg and LHV_{H_2} is the lower heating value of hydrogen fuel in kJ/kg.

The BSEC was calculated depending on lower heating values of gasoline and hydrogen, mass flow of supplied fuels and the engine brake power [31]:

$$BSEC = \frac{\dot{m}_g \times LHV_g + \dot{m}_{H_2} x LHV_{H_2}}{P_b}, \tag{5}$$

where BSEC is the brake specific energy consumption in MJ/kWh, $\dot{m}_g$ is the mass flow of supplied gasoline fuel in kg/s, $\dot{m}_{H_2}$

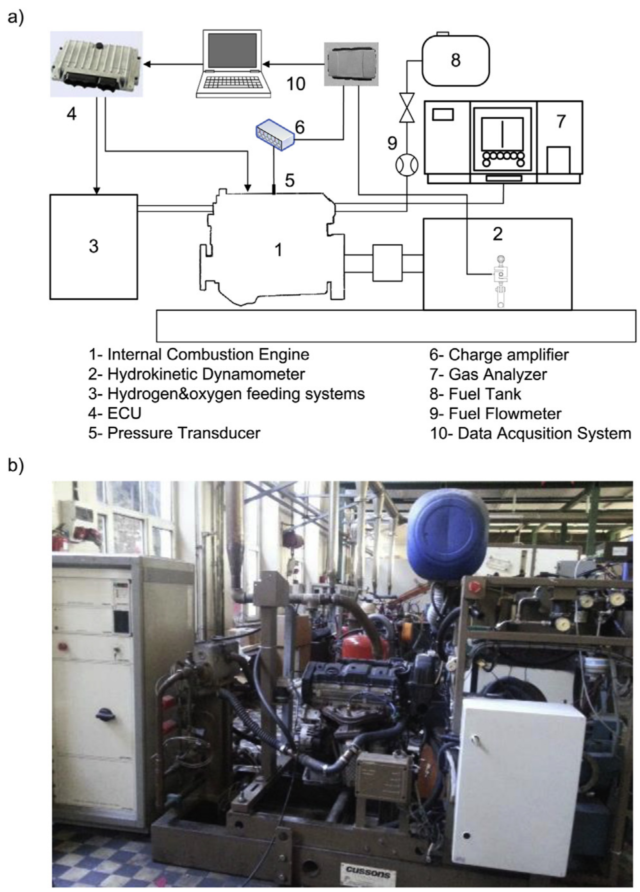

Fig. 2 – a) Schematic diagram of experimental setup. b) Overview of the test engine.

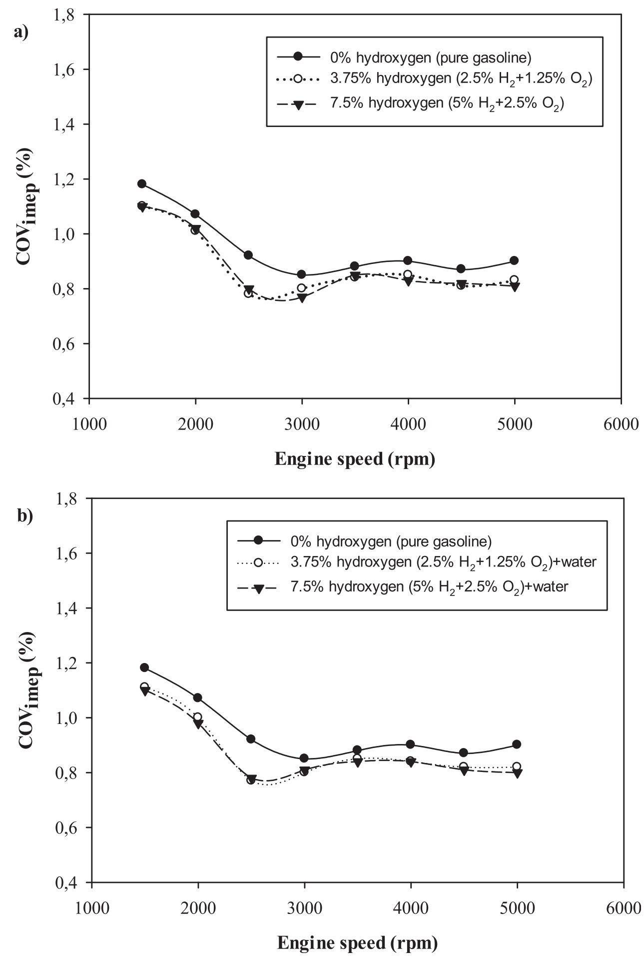

Fig. 3 – a) Variation of COVimep versus engine speed with hydroxygen enrichment at 50% throttle position. b) Variation of COVimep versus engine speed with hydroxygen + water enrichment at 50% throttle position.

is the mass flow of supplied hydrogen fuel in kg/s, LHV_g is the lower heating value of gasoline in MJ/kg and LHV_{H_2} is the lower heating value of hydrogen in MJ/kg.

The total measurement uncertainties were calculated according to Kline and McClintock method [28] for entire speed as following equation:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2}, \tag{6}$$

where W_R is the calculated uncertainty result, R is a given function, x_1, x_2, …,x_n are the independent variables of the function and w_1, w_2, … w_n are the uncertainty values in the independent variables.

Table 2 – Measurement accuracies of the devices and the calculated uncertainties of the results.

Measured parameter	Device	Accuracy
Engine torque	Load cell	±0.05 Nm
Engine speed	Incremental encoder	±5 rpm
In-cylinder pressure	Kistler 6118B	±0.3 bar
Fuel flow rate	Sika VZ 0.2	±1% (of reading)
Hydrogen mass-flow rate	New-flow TMF00	±1% (F.S.)
Oxygen mass-flow rate	New-flow TMF01	±1% (F.S.)
CO	AVL Dicom 4000	±0.01 vol%
THC	AVL Dicom 4000	±1 ppm
NO_x	AVL Dicom 4000	±1 ppm
Results		Calculated uncertainties (for whole speed range)
Brake Power		±0.09% ÷ 0.12%
BSEC		±1.11% ÷ 1.34%

Results and discussion

An experimental investigation was done on the performance characteristics of a hydroxygen enriched gasoline engine and also water injection into the intake air was investigated in case of hydrogen enrichment. All of the tests were performed at the Internal Combustion Engines Laboratory in Yıldız Technical University. The test bench and the test engine were adapted to operate with hydroxygen and water. In previous study, Karagoz et al. [32] investigated the effect of 0% hydroxygen (pure gasoline), 4.5% hydroxygen (3% H_2 + 1.5% O_2) and 9% hydroxygen (6% H_2 + 3% O_2) on performance and emissions of an SI engine of total intake air by volume addition between 1500 and 3500 rpm engine speed. They controlled hydrogen and oxygen flow rates with needle valves. In this study, different percentage of hydroxygen flow rates; 0% hydroxygen (pure gasoline), 3.75% hydroxygen (2.5% H_2 + 1.25% O_2) and 7.5% hydroxygen (5% H_2 and 2.5% O_2) were investigated in a gasoline engine between 1500 and 5000 rpm engine speed. Also, the effect of water injection (25% of gasoline mass flow rate) on engine performance and emissions were investigated in this work. Multipoint sequential gas injection system and a single point water injector were used in this experimental study. Also, a self-developed ECU was used to trigger water injector and gas injectors. Furthermore, COV_{imep} values were calculated using in-cylinder pressure data to investigate cycle by cycle variations. Our aim is to investigate the effect of hydroxygen enrichment and water addition together in this work.

The cyclic variation is important since it determines the engine stability. The most frequently used parameter to determine cyclic variation is the coefficient of variation according to imep (COV_{imep}) [19]. Acceptable percentage is lower than 10% in terms of comfort criteria [33]. Also, based on Lyon's work [34], if cyclical differences in engine are reduced, thermic efficiency can be increased up to 6%. The variation of COV_{imep} values versus engine speed with hydroxygen enrichment was shown in Fig. 3a, and the variation of COV_{imep} values versus engine speed with hydroxygen and water enrichment are depicted in Fig. 3b. In both graphs, pure gasoline condition exists. Hydroxygen addition has positive effect on COV_{imep} for whole engine speed. Also, COV_{imep} values were reduced with addition of hydroxygen independently from hydrogen level. Moreover, in case of water + hydroxygen addition, the COV_{imep} values are still lower than pure gasoline but slightly higher than only hydroxygen addition. COV_{imep} variations are insignificant according to engine speeds after 2000 rpm for all of the hydroxygen enrichment and hydroxygen + water enrichment levels. In study of Sun et al. [35], it is found out that engine speed does not have an important role on COV_{imep} in engines operated by hydrogen. For first condition, 3.75% hydroxygen is added; a reduction between 15.2% and 4.5% is seen on COV_{imep} value compared to gasoline (0% hydroxygen). For second condition, 7.5% hydroxygen is added, a reduction between 13.1% and 4.6%. For third condition, 3.75% hydroxygen + water is added, a reduction of 16.3%–3.4% is observed on COV_{imep} value compared to gasoline (0% hydroxygen). With 7.5% hydroxygen + water addition, a reduction of 15.2%–4.5% is observed. The reason can be explained by higher flame speed of hydrogen and thus combustion duration may decrease with hydrogen addition [19]. Thanks to improved COV_{imep} values with hydroxygen addition; the engine can reach high thermal efficiency and performance values. The results of D'Andrea et al. [33] and Ji and Wang [19] are similar with the results of this study. Also, Subramanian et al. [27] found that water injection does not have noticeable effect on COV_{imep} and in this study; the effect of water injection is negligible.

The variation of brake power generated by the test engine versus engine speed with hydroxygen enrichment was illustrated in Fig. 4a and the variation of brake power generated by the test engine versus engine speed with hydroxygen + water enrichment was shown in Fig. 4b. In both graphs, pure gasoline condition exists. Hydroxygen addition has a positive effect on the power output of the test engine for entire speed range. Especially for low engine speeds hydroxygen has greater effect on brake power than high engine speeds. With water injection, brake power values were slightly decreased but still they were higher than pure gasoline. Brake power increased by 11.2%–1.6% respectively with 3.75% hydroxygen and 7.5% hydroxygen addition Brake power increased by

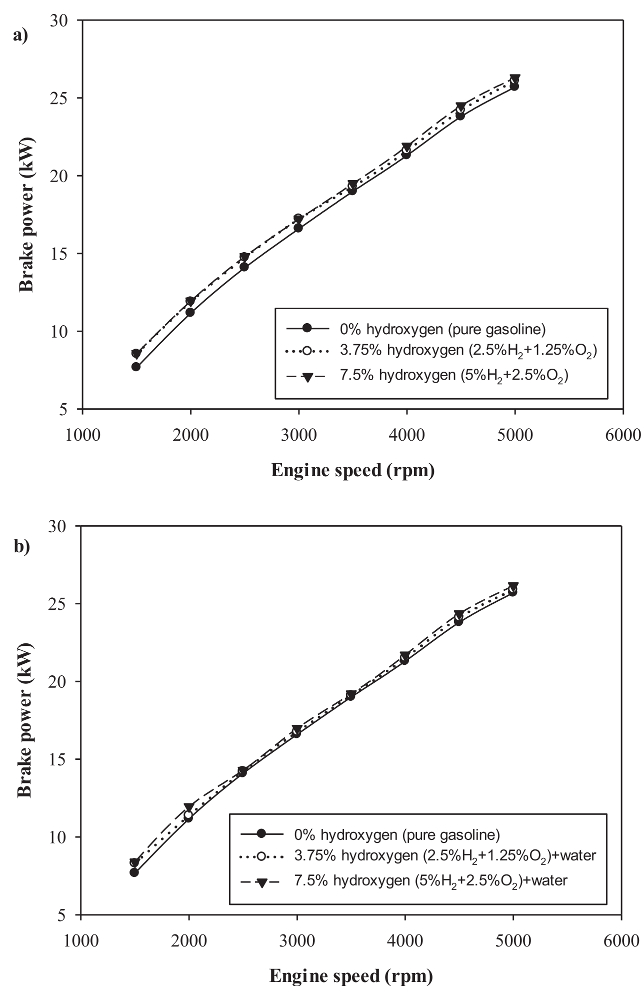

Fig. 4 – a) Variation of brake power versus engine speed with hydroxygen enrichment. b) Variation of brake power versus engine speed with hydroxygen + water enrichment.

11.7%–2.3% for gasoline (0% hydroxygen addition) and brake power increased by 8.2%–0.8% and 9.5%–1.1% respectively with 3.75% hydroxygen + water addition and 7.5% hydroxygen + water addition. The lower heating value per kg of hydrogen is higher than gasoline which causes an increase on brake power [30]. Also, higher flame speed of hydrogen can stimulate the combustion period and higher in-cylinder pressure is obtained. Thus, increase of brake power is related with the rise of overall efficiency, which comprises thermodynamic and combustion efficiency all together [23]. The BMEP result of Ji and Wang [19] and the torque results of D'Andrea et al. [33] are similar with this study. High specific heat capacity and high value of vaporization latent heat of water reduces the charge temperature which causes a reduction in-cylinder temperature and in-cylinder pressure [27]. In this study, little water was injected and consequently a slight decrease in generated power of the test engine occurred.

Fig. 5a shows the variation of brake thermal efficiency versus engine speed with hydroxygen enrichment, and Fig. 5b depicts variation of brake thermal efficiency versus engine speed with hydroxygen + water enrichment. Results obtained by pure gasoline use are placed on both graphs. The brake

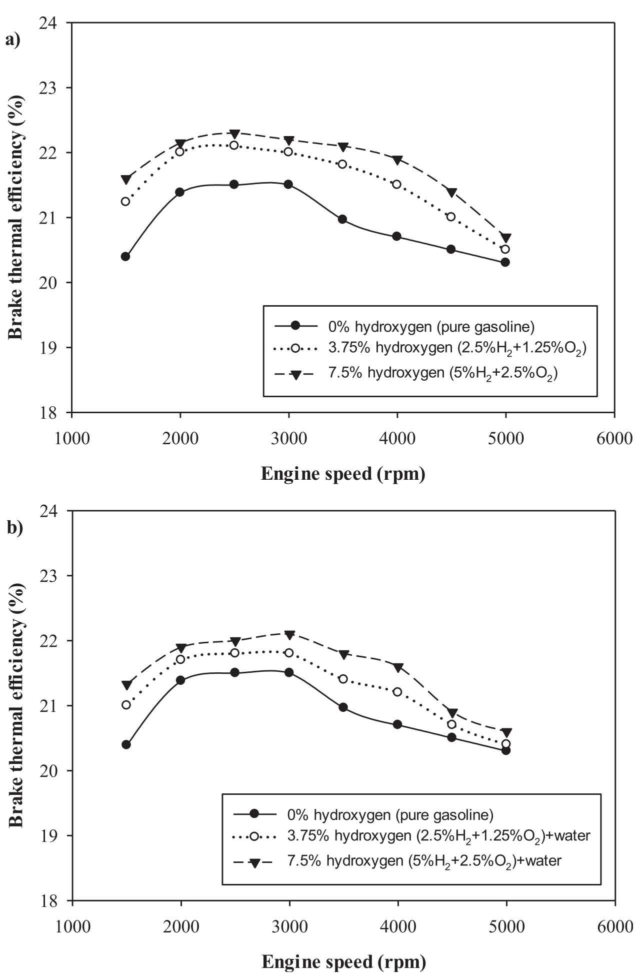

Fig. 5 – a) Variation of brake thermal efficiency versus engine speed with hydroxygen enrichment. b) Variation of brake thermal efficiency versus engine speed with hydroxygen + water enrichment.

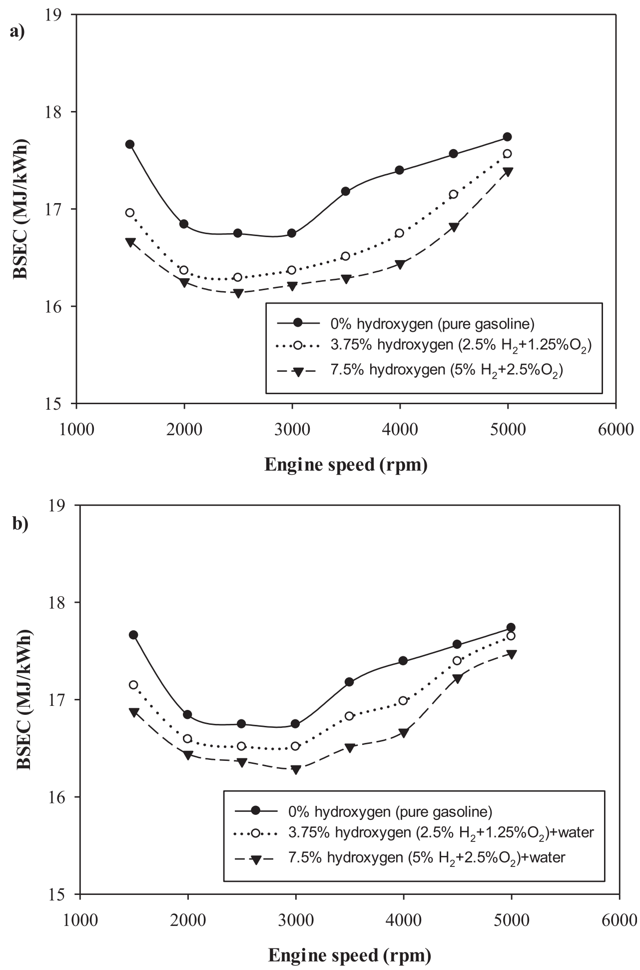

Fig. 6 – a) Variation of BSEC versus engine speed with hydroxygen enrichment. b) Variation of BSEC versus engine speed with hydroxygen + water enrichment.

thermal efficiency values were increased with hydroxygen enrichment but it was decreased with water injection. However, in case of hydroxygen + water addition the brake thermal efficiency was still higher than pure gasoline. The maximum increase in brake thermal efficiency was found at lowest engine speed (1500 rpm) and 4000 rpm (about the maximum torque engine speed) for both hydroxygen and hydroxygen + water enrichment cases. An improvement on brake thermal efficiency value is observed by 1%–4.2%, 2%–5.9%, 1%–3% and 1.5%–4.4% respectively with 3.75% hydroxygen, 7.5% hydroxygen, 3.75% hydroxygen + water and 7.5% hydroxygen + water addition compared to pure gasoline. Hydrogen has higher flame speed than gasoline (about 5 times) and higher burning speed improves thermal efficiency [36]. Also, hydrogen has wider flammability limits than gasoline. For these reasons, hydrogen enriched gasoline mixture fuel will achieve shorter burning continuance and more complete combustion can be seen. Thus, constant volume combustion can happen which means the SI engine is much closer to ideal cycle thanks to faster burning speed of hydrogen-gasoline blends. On the other hand, hydrogen addition can increase peak in-cylinder temperature and in-

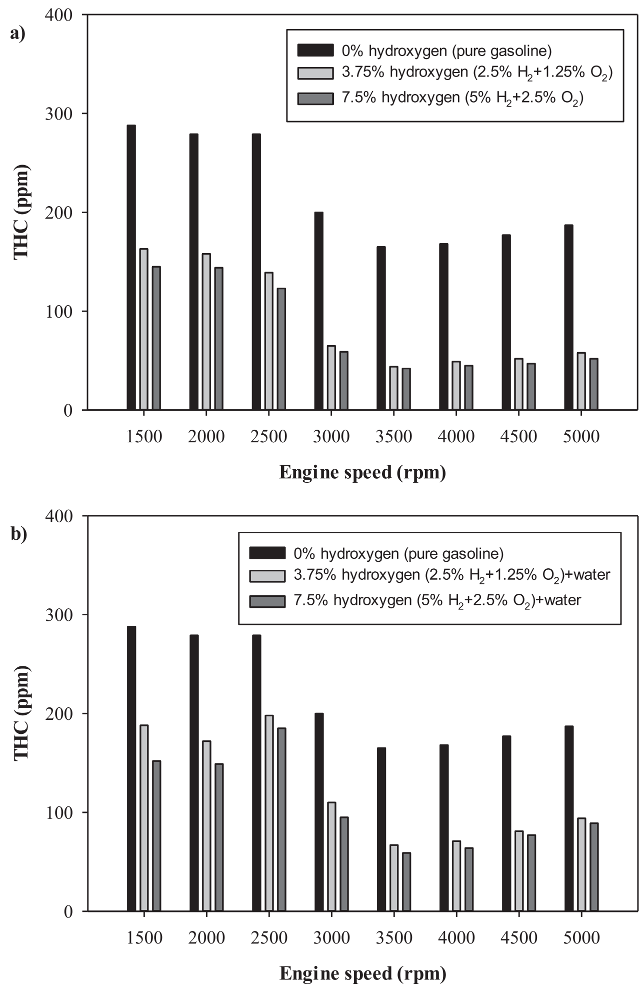

Fig. 7 – a) Variation of THC emission versus engine speed with hydroxygen enrichment. b) Variation of THC versus engine speed with hydroxygen + water enrichment.

cylinder pressure. However, instantaneous pressure rise and drops are observed in hydrogen enriched gasoline engines which limit post combustion period. Thus, reduced exhaust losses are obtained [19]. Also, shortened combustion period reduces cooling loss of engine [23]. Furthermore, oxygen concentration increases with hydroxygen enrichment which allows to air-fuel blends to be burnt completely [23]. Ji and Wang [19] and Wang et al. [23] found similar results with this study. However, with water injection vaporization absorbing heat causes to put down peak in-cylinder temperature because of the high heat capacity of water [37]. For this reason, a slight decrease is observed with water addition. During the tests, ignition advance of the test engine was not changed, and hence optimum ignition timing was not investigated for all test fuels. Further improvement of thermal efficiency can be possible with optimized ignition timings.

BSEC can be explained by the amount of consumed energy in MJ per generated engine power in kW by the gasoline engine. Total energy consumption was used to calculate BSEC. Since fuels (hydrogen and gasoline) have different lower heating values and densities, BSEC can evaluate more accurately than brake specific fuel consumption, Fig. 6a depicts the variation of BSEC versus engine speed with hydroxygen addition, and Fig. 6b the variation of BSEC versus engine speed with hydroxygen + water addition. Pure gasoline results are depicted on both graphs. BSEC was improved with hydroxygen addition. BSEC increased entire engine speed with hydroxygen and hydroxygen + water addition. Best BSEC was observed in 3.75% of $H_2 + O_2$ addition at 3500 rpm engine speed which is in harmony with brake power measurements. Water addition reduced the improvement of BSEC. BSEC decreased by 1%–4% and 1.9%–5.6% with 3.75% hydroxygen and 7.5% hydroxygen addition compared to pure gasoline. Moreover, BSEC decreased by 0.5%–2.9% and 1.5%–4.4% with 3.75% hydroxygen + water addition and 7.5% hydroxygen + water addition compared to pure gasoline. Hydrogen has higher laminar flame speed than gasoline which causes an increase on peak-in cylinder pressure [3]. Enhanced constant volume combustion which is close to ideal cycle is obtained thanks to higher flame speed of hydrogen and wider flammability limits [3]. Furthermore, higher flame speed of hydrogen reduces combustion duration which means exhaust and cooling losses reduce [23]. The results of this study are similar with works of Ji and Wang [19] and Wang et al. [23]. On the other hand, the vaporization of water can reduce the combustion temperature [37]. It also improves specific heat capacity and latent heat vaporization of charge [27]. For these reasons, a slight increase is obtained from test results.

Incomplete combustion of hydrocarbon fuels causes creation of hydrocarbons which are organic compounds. The unburned hydrocarbon in the tail-pipe gases is generally called as total hydrocarbon (THC) [10]. The variation of THC emission versus engine speed with hydroxygen enrichment was illustrated in Fig. 7a, and the variation of THC emission versus engine speed with hydroxygen + water enrichment was illustrated in Fig. 7b. A great improvement was observed all the levels of hydroxygen addition. A slight increase was observed in THC emission with water addition but still a great improvement was seen according to pure gasoline fuel. The THC emissions firstly decrease, and then a slight increase was observed with increases in engine speed for all of the hydroxygen and water enrichment levels. An improvement of 70.8% and 74.5% respectively is observed on THC emissions with 3.75% hydroxygen and 7.5% hydroxygen addition. An improvement of 59.4% and 64.2% respectively is observed with 3.75% hydroxygen + water addition and 7.5% hydroxygen + water addition compared to pure gasoline. This improvement is seen at 3500 rpm engine speed condition. According to the results, it can be stated that a great decrease on THC was achieved through usage of hydrogen as supplementary fuel due to reduction of the hydrocarbon portion in fuel mixture. On the other hand, increase of thermal efficiency and decrease of THC can be a consequence of improved combustion due to higher flame speed of hydrogen when compared to gasoline. Also, the formation of OH radicals will accelerate because of the improvement in chain reaction and more complete combustion which decrease THC emissions [23]. Furthermore, the quenching distance of hydrogen is lower than gasoline which means that the hydrogen flame can propagate closer to cylinder wall [19]. Flame extinguishment

and cravis effect improve with hydrogen addition and consequently the engine emits less THC emission. THC emission improvement becomes important at medium and high engine speeds which reduced up to 42 ppm with 7.5% hydroxygen enrichment level. The results of this study are consistent with the results of Wang et al. [23] and Ji and Wang [23]. With addition of little water, the reduction in pre-combustion temperature occurs [38]. It causes a lower in-cylinder temperature and consequently combustion efficiency is negatively effected and a slight increase was obtained in this study.

Nitric oxide (NO) and nitrogen dioxide (NO_2) are usually grouped together as nitrogen oxides (NO_x) and exhaust emission contain the oxides of nitrogen [10]. NO is produced inside the cylinder and the principal source of NO is the oxidation of atmospheric nitrogen [10]. Fig. 8a shows the variation of NO_x emissions versus engine speed with hydroxygen enrichment, and Fig. 8b depicts variation of NO_x versus engine speed with hydroxygen + water enrichment. With hydroxygen addition, NO_x emissions were dramatically increased. Water injection technique decreased NO_x emissions. However, NO_x emissions are still higher from pure gasoline level. In order not to increase CO and THC levels and BSEC, the mass-flow rate of water was kept constant at 25% of the gasoline mass-flow rate.

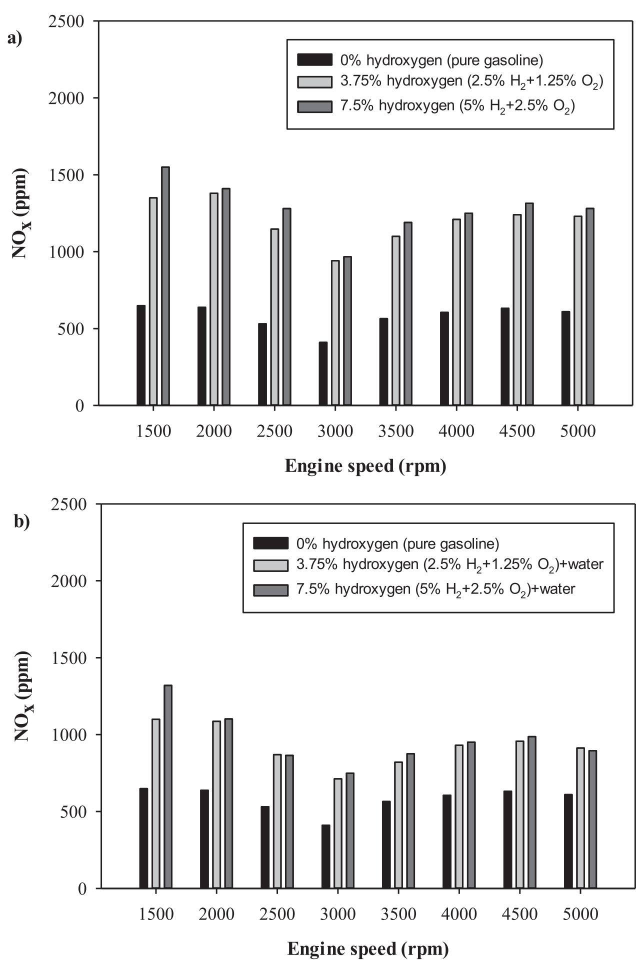

Fig. 8 – a) Variation of NO_x emissions versus engine speed with hydroxygen enrichment. b) Variation of NO_x versus engine speed with hydroxygen + water enrichment.

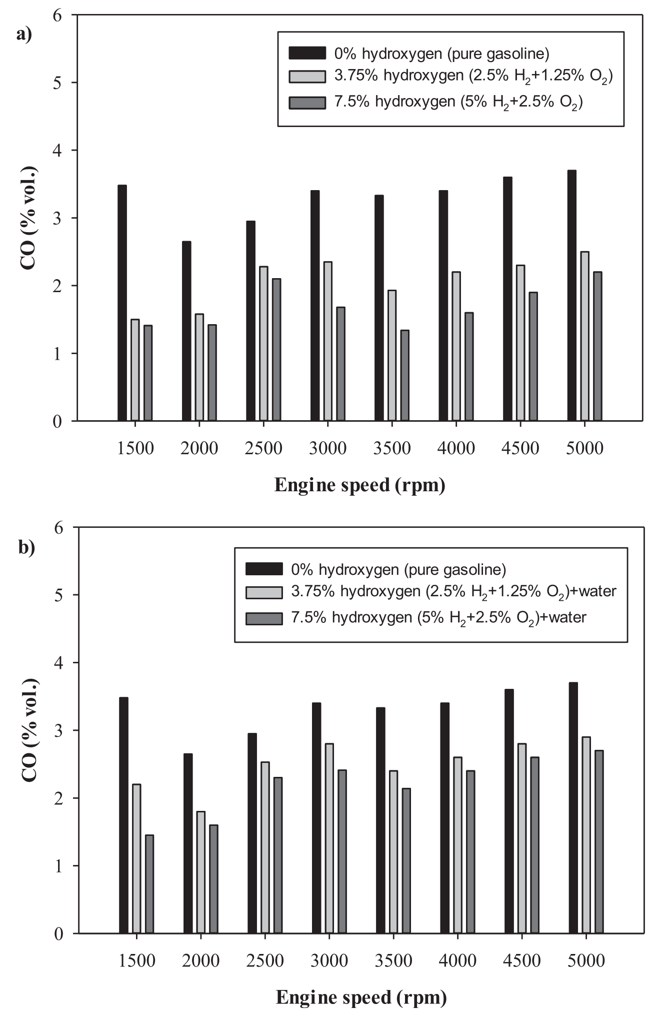

Fig. 9 – a) Variation of CO emission versus engine speed with hydroxygen enrichment. b) Variation of CO versus engine speed with hydroxygen + water enrichment.

NO_x emissions increased by 94.7%–129.5% and 106.6%–141.1% respectively with 3.75% hydroxygen and 7.5% hydroxygen addition. This dramatical increase on NO_x emissions is reduced by water pulverization. Still, there is an increase of 45.3%–70.2% and 54.9%–87.2% respectively on NO_x emissions with 3.75% hydroxygen + water pulverization and 7.5% hydroxygen + water pulverization compared to gasoline. Oxides of nitrogen formation is highly depending on both high temperature and oxygen availability [10]. With hydroxygen addition, the availability of oxygen and higher in-cylinder temperature is obtained. Also, rapid combustion of hydrogen significantly decreased THC although the inverse effect of this type of combustion can be seen on nitrogen oxides results. Hydrogen acts like an igniter for intake charge due to its high flame speed which increases in-cylinder temperature and hence nitrogen oxide emissions increased significantly [19]. Wang et al. [23] and D'Andrea et al. [33] obtained similar results on their study. Due to high molar heat capacity of water and the high level of heat absorption during vaporization of water, it minimizes peak combustion temperature and consequently it reduces oxides of nitrogen formation [37]. The

result of this study is similar with the results of Tesfa et al. [38] and Cesur et al. [39] in terms of water addition.

Carbon monoxide (CO) is a colourless, odourless and tasteless gas and it is noxious. CO is produced by partial oxidation of carbon containing compounds, and if there is not enough oxygen to produce carbon dioxide (CO_2), it will be formed [10]. If the oxygen (O_2) availability improves, the formed CO will be oxidized further to CO_2 formation [10]. (a) Fig. 9a shows the variation of CO emission versus engine speed with hydroxygen enrichment; Fig. 9b depicts the variation of CO emission versus engine speed with hydroxygen + water enrichment. Pure gasoline condition exists on both graphs. As it can be seen, a great improvement in CO emission is observed at all of the engine speeds. Decrease in CO emissions with hydroxygen addition considering pure gasoline fuel was higher than hydroxgen + water addition. A reduction by 56.9%–22.7% and 59.5%–28.8% respectively is observed with 3.75% hydroxygen and 7.5% hydroxygen addition and a reduction by 36.8%–14.2% and 58.3%–22.0% respectively with 3.75% hydroxygen + water and 7.5% hydroxygen + water addition. Hydrogen is a carbon-free fuel, so when hydrogen enriched gasoline used as fuel in SI engine, it produces less carbon monoxide [22]. Also, higher flame speed, higher diffusion rate in air and wider flammability range of hydrogen than gasoline improves combustion efficiency and more complete combustion is achieved with hydrogen assisted gasoline combustion [3]. The improved in-cylinder temperature with hydrogen addition stimulates oxidation reaction, thus more CO are oxidized to CO_2 with hydrogen addition [19]. The results of this study are consistent with the results of Ji and Wang [19]. The reduction in pre-combustion temperature bacause of the water addition causes to worsen chemical conversion of CO to CO_2. Moreover, solid carbon reaction with water happens to ameliorate formation of CO [38]. Tesfa et al. [38] are obtained similar result with this study in terms of water addition.

Conclusions

The focus of this experimental study is to investigate the effects of hydroxygen usage as supplementary fuel and water injection method in SI engines, from the perspective of performance and emissions. Hydroxygen ($H_2 + O_2$) supplementary fuel was injected into intake ports of the test engine with the ratio of 0% (pure gasoline), 3.75% (2.5%H_2 + 1.25%O_2) and 7.5% (5%H_2 + 2.5% O_2) by volume of intake charge respectively. Additionally, water (25% of gasoline mass flow rate) was injected into intake manifold with 3.75% hydroxygen, and 7.5% hydroxygen enrichment to decrease NO_x emissions. Throttle was set to constant 50% position and engine loaded with a hydrokinetic dynamometer. Engine brake power and tail-pipe emissions were measured. Usage of hydrogen as supplementary fuel provided improved engine performance and emissions characteristics, although nitrogen oxides were increased. Detailed assessment of test results and conclusions are given as following:

- The maximum increase in brake power was 11.2% and 11.7% higher than pure gasoline with 3.5% and 7.5% hydroxygen enrichment.
- Engine thermal efficiency improved for both of the hydroxygen ($H_2 + O_2$) injection rates. Best thermal efficiency was observed in 7.5% of hydroxygen addition at 1500 rpm and 4000 rpm engine speeds which are 5.9% and 5.8% higher compared to pure gasoline operation.
- A dramatic decrease of THC was observed with hydroxygen addition which especially becomes important at medium and high engine speeds. Total hydrocarbon emissions reduced up to 42 ppm at 3500 rpm engine speed.
- A great improvement in CO emission observed at all of the engine speeds. The maximum decrease in CO emission was obtained 59.5% with 7.5% $H_2 + O_2$ addition at 1500 rpm engine speed.
- NO_x emissions increased by 94.7%–129.5% and 106.6%–141.1% respectively with 3.75% hydroxygen and 7.5% hydroxygen addition. This dramatical increase on NO_x emissions is reduced by water pulverization. Still, there is an increase of 45.3%–70.2% and 54.9%–87.2% respectively on NO_x emissions with 3.75% hydroxygen + water pulverization and 7.5% hydroxygen + water pulverization compared to gasoline.

Acknowledgement

This research was supported by the Yıldız Technical University Scientific Research Projects Coordination Department. Project Number: 2011-06-01-YULAP01. Also, the authors are indebted to Tek Oto Company (Peugeot dealer in Istanbul, Turkey) for SI engine donation.

Nomenclature

BSEC	brake specific energy consumption
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variation
ECU	electronic control unit
H_2	hydrogen molecule
IC	internal combustion
ICE	internal combustion engine
imep	indicated mean effective pressure
LPG	liquefied petroleum gas
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
O_2	oxygen molecule
SI	spark ignition
THC	total unburned hydrocarbons

REFERENCES

[1] Nieminen J, D'Souza N, Dincer I. Comparative combustion characteristics of gasoline and hydrogen fuelled ICEs. Int J Hydrogen Energy 2010;35(10):5114–23.

[2] Al-Baghdadi MARS, Al-Janabi HAKS. Improvement of performance and reduction of pollutant emission of a four

stroke spark ignition engine fueled with hydrogen-gasoline fuel mixture. Energy Convers Manag 2000;41(1):77–91.
[3] Ji CW, Wang SF. Effect of hydrogen addition on the idle performance of a spark ignited gasoline engine at stoichiometric condition. Int J Hydrogen Energy 2009;34(8):3546–56.
[4] Ganeshb RH, Subramaniana V, Balasubramanianb V, Mallikarjuna JM, Ramesh A, Sharma RP. Hydrogen fueled spark ignition engine with electronically controlled manifold injection: an experimental study. Renew Energy 2008;33:1324–33.
[5] Janabi AI, Baghdadi AI. A prediction study of the effect of hydrogen blending on the performance and pollutants emission of a four stroke spark ignition engine. Int J Hydrogen Energy 1999;24:363–75.
[6] Yousufuddin S, Masood M. Effect of ignition timing and compression ratio on the performance of a hydrogen ethanol fuelled engine. Int J Hydrogen Energy 2009;34:6945–50.
[7] Rakopoulos CD, Kyritsis DC. Hydrogen enrichment effects on the second law analysis of natural and landfill gas combustion in engine cylinders. Int J Hydrogen Energy 2006;31:1384–93.
[8] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energy Combust Sci 2009;35(6):490–527.
[9] Lancaster DR, Krieger RB, Sorenson SC, Hull WL. Effects of turbulence on spark-ignition engine combustion. 1976. SAE Paper No. 760160.
[10] Heywood JB. Internal combustion engine fundamental. New York: McGraw-Hill, Inc.; 1988.
[11] Sopena C, Dieguez PM, Sainz D, Urroz JC, Guelbenzu E, Gandia LM. Conversion of a commercial spark ignition engine to run on hydrogen: performance comparison using hydrogen and gasoline. Int J Hydrogen Energy 2010;35(3):1420–9.
[12] Ceper BA, Akansu SO, Kahraman N. Investigation of cylinder pressure for H_2/CH_4 mixtures at different loads. Int J Hydrogen Energy 2009;34(11):4855–61.
[13] Karim GA. Hydrogen as a spark ignition engine fuel. Int J Hydrogen Energy 2003;28(5):569–77.
[14] D'Andrea T, Henshaw P, Ting DSK. The addition of hydrogen to a gasoline-fuelled SI engine. Int J Hydrogen Energy 2004;29(14):1541–52.
[15] Apostolescu N, Chiriac R. A study of combustion of hydrogen-enriched gasoline in a spark ignition engine. SAE International; 1996.
[16] Bauer CG, Forest TW. Effect of hydrogen addition on the performance of methane-fueled vehicles. Part I: effect on S.I. engine performance. Int J Hydrogen Energy 2001;26:55–70.
[17] Lucas GG, Richards WL. The hydrogen/petrol engine the means to give good part-load thermal efficiency. 1982. SAE Paper No. 820315.
[18] May H, Gwinner D. Posibilities of improving exhaust emissions and energy consumption in mixed hydrogen-gasoline operation. Int J Hydrogen Energy. 1983;8:121–9.
[19] Ji C, Wang S. Effect of hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions. Int J Hydrogen Energy 2009;34:7823–34.
[20] Abdel HK, Sadik M, Bassyouni M, Shalabi M. A new approach to utilize hydrogen as a safe fuel. Int J Hydrogen Energy 2005;30:1511–4.
[21] Dulger Z, Ozcelik KR. Fuel economy improvement by on board electrolytic hydrogen production. Int J Hydrogen Energy 2000;25:895–7.
[22] Bari S, Esmaeil MM. Effect of H_2/O_2 addition in increasing the thermal efficiency of a diesel engine. Fuel 2010;89:378–83.
[23] Wang S, Ji C, Zhang B, Liu X. Performance of a hydroxygen-blended gasoline engine at different hydrogen volume fractions in the hydroxygen. Int J Hydrogen Energy 2012;37:13209–18.
[24] Lee JT, Kim YY, Lee CW. An investigation of a cause of backfire and its control due to crevice volumes in a hydrogen fuelled engine. Trans ASME 2001;123:204–10.
[25] Lee SJ, Yi HS, Kim ES. Combustion characteristic of intake port injection type hydrogen fuelled engine. Int J Hydrogen Energy 1995;20(4):317–22.
[26] Bohacik T, DeMaria S, Saman WY, et al. Constant volume adiabatic combustion of stoichiometric hydrogen oxygen mixtures. J Renew Energy 1996;9:1254–7.
[27] Subramanian V, Mallikarjuna JM, Ramesh A. Effect of water injection and spark timing on the nitric oxide emission and combustion parameters of a hydrogen fuelled spark ignition engine. Int J Hydrogen Energy 2007;32:1159–73.
[28] Kline SJ, McClintock FA. Describing uncertainties in single-sample experiments. Mech Eng 1953;75:3–8.
[29] Kahraman E, Ozcanlı SC, Ozerdem B. An experimental study on performance and emission characteristics of a hydrogen fuelled spark ignition engine. Int J Hydrogen Energy 2007;32:2066–72.
[30] Köse H, Ciniviz M. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Process Technol 2013;114:26–34.
[31] Liu J, Yao A, Yao C. Effects of injection timing on performance and emissions of a HD diesel engine with DMCC. Fuel 2014;134:107–13.
[32] Karagoz Y, Orak E, Sandalci T, Uluturk M. Effect of H_2^+ O_2 gas mixture addition on emissons and performance of an SI engine. Mach Technol Mater 2012;7:38–43.
[33] D'Andrea T, HenshawD PF, Ting S-K and Sobiesiak A, Investigating combustion enhancement and emissions reduction with the addition of $2H_2 + O_2$ to a SI engine. SAE Pap No. 2003-32-0011.
[34] Li JD, Guo LS, Du TS. Formation and restraint of toxic emissions in hydrogen–gasoline mixture fueled engines. Int J Hydrogen Energy 1998;23:971–5.
[35] Sun B, Zhang D, Liu F. Cycle variations in a hydrogen internal combustion engine. Int J Hydrogen Energy 2013;38:3778–83.
[36] Swain MR, Yusuf MJ, Dulger Z, et al. The effect of hydrogen addition on natural gas engine operation. 1993. SAE paper No. 932775.
[37] Lin CY, Wang KH. Effects of diesel engine speed and water content on emission characteristics of three-phase emulsions. J Environ Sci Health Part A 2004;39(5):1345–59.
[38] Tesfa B, Mishra R, Gu F, Ball AD. Water injection effects on the performance and emission characteristics of a CI engine operating with biodiesel. Renew Energy 2012;37:333–44.
[39] Cesur I, Parlak A, Ayhan V, Boru B, Gonca G. The effects of electronic controlled steam injection on spark ignition engine. Appl Therm Eng 2013;55:61–8.